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Getting Ready for Carbon Capture and Storage in the Iron and Steel Sector in China: Assessing the Value of Capture Readiness

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Abstract

China's steel sector, contributing 40% of world steel production, are moving the plants out of highly-populated areas in China. Carbon capture and storage (CCS) is an important technology to achieve a deep reduction of emissions in steel plants. Given by high cost and lack of policy incentive in deploying the CCS process, there has been a lack of progress in CCS within the steel sector in China. Capture readiness is a design concept to ease future CCS retrofit and avoid the carbon lock-in effect in steel plants. Capture Readiness design requires moderate upfront investment, i.e. less than 0.5% additional capital expenditure, but could easily enable the plant to be retrofitted with CCS technologies in their lifetime. The paper develops a novel linear programming model to assess the economic cost of Capture Readiness design in a generic steel plant in China. The Baowu Steel Zhanjiang project was used as a reference plant to develop the generic steel plant for the model. Through a Monte Carlo simulation, the results show that the economic cost of making new steel plants in capture readiness for 0.5 million tonnes capture is CNY 65 million (USD 9.5 million) in a conservative 5% carbon price growth rate scenario. The paper found the value of flexibility brought by capture readiness design is significant and is equal to approximately 15% of initial capital investment. The economically viable chance of retrofitting steel plants with CCS technologies in the lifetime is 49%. In an uncertainty analysis, for a 6% growth rate of carbon price, the option value could be increased to CNY 145 million while the probability of retrofit increases to 79%. China's CCS policy should consider a requirement for newly built steel plants to adopt capture readiness design to capture the significant economic value and ease emissions reduction in the iron and steel sector in the long term.

Key Words: Capture Readiness, Steel, CCS, China, Real Option

Highlights

- This is the first study investigating CCS readiness in the iron and steel sector
- Capture readiness steel plant can ease retrofit processes with carbon capture and storage in a plant's lifetime
- The paper proposes the key criteria for designing a CCS readiness steel plant
- A novel model is developed in assessing the value of capture readiness
- The retrofit option value of a steel plant is significantly higher than the estimated additional cost for making a steel plant CCS readiness

1. Introduction

Climate change has become a global challenge, and how to mitigate greenhouse gas emissions from industrial system is the key question. The Paris Agreement in 2015 established an global action plan to mitigate climate change to limit global warming in the long-term to well below 2°C compared to pre-industrial levels, and to pursue best efforts to limit increased warming to 1.5°C [UNFCCC, 2015]. The 2°C target represents that global emissions must be reduced per capita from 7tCO2 per annum to 4tCO2 in 2030, and 2tCO2 in 2050 (ADB, 2015). IEA (2017) suggests that CCS (Carbon Capture and Storage, also called "Carbon Capture Utilisation and Stoarge, CCUS") could contribute 14% of greenhouse gas emission reductions between 2010 and 2050 for the 2 degrees scenario (2DS) and 32% for the beyond 2 degrees scenario (B2DS).

China has been a major contributor to the world's climate mitigation process. In 2016, the estimated emissions from fossil fuels in China was estimated to be equivalent to approximately 1% of the remaining carbon budget (Janssens-Maenhout et al, 2017). China's Intended Nationally Determined Contribution (INDC) to the Paris Agreement includes targets for carbon dioxide emissions to peak by around 2030 (with best efforts to peak earlier), to lower carbon dioxide emissions per unit of GDP by 60-65% from 2005 levels by 2030, and to increase the share of non-fossil fuels in primary energy consumption to around 20% by 2030 (NDRC, 2015a). The INDC outlines a portfolio of low-carbon technologies and mechanisms to reduce greenhouse gas emissions, including setting up a national carbon market. Furthermore,

CCS has been emphasized as a key technology to help achieve emission reduction target in a large number of government's policy documents in China (NDRC, 2015b). The Chinese government has 10 years of experience in supporting CCS research, development and demonstration through various policy mechanisms (appendix 1). With moderate policy incentive support, CCS could be an economic viable approach that contributes to 20% of greenhouse gas emissions in China in 2030 (Chen et al, 2016). Current applications of carbon capture projects in China primarily used amine base post-combustion capture technologies for low concentration sources (such as flue gases in the power sector, steel sector, cement sector) and pressurized swing absorption (PSA) for high purity CO2 sources (such as coal gasification, gas reforming plants). The cost of separating CO2 from low concentration sources is still much higher than carbon allowance prices in China's pilot carbon markets. Energy penalty is also a major barrier for deploying CCS at large-scale in China (Liang and Reiner, 2013). Providing above challenges, even though CCS has a crucial role in mitigating climate change, the technology has not been fully understood by stakeholders (Wennerstern et al, 2015).

Although the iron/steel industry has become a mitigation target in the past decade, it is still one of the most energy-intensive and carbon-intensive industries, as only fossil fuel consumption can provide efficient and affordable energy for the iron- and steel-making processes. The consequence of the amount of fossil fuel consumption is emitting a significant amount of CO2 into the atmosphere (Quader et al, 2015). The iron/steel industry contributes approximately 22% of total industrial energy use and 31% industrial direct emissions in 2012 (IEA, 2015). CCS is a key technology that could decarbonize the iron and steel sector while CCS with biomass could potentially contribute to develop a carbon neutral iron and steel sector (Mandova et al, 2019).

China's steel sector contributed 44% of global crude steel production in 2015 (World Steel Association, 2016). Although the production of crude steel in China has been reduced in recent years, there is a likely long-term growth of global crude steel production. The EU Commission's Low Carbon Roadmap anticipates a global emission intensity of no more than 0.2 tCO2 per tonne of crude steel by the end of 2050, compared to the EU's current level of above 1.3 tCO2 per tonne crude steel, and China's average of 2.18 tCO2 per tonne in 2014 (Zou et al, 2013). The Roadmap suggests CCS is a key technology to meet a more ambitious emission reduction target in the iron/steel sector.

Even though China has been the largest crude steel producer since 2003, there are no CCS pilot or demonstration projects in the steel sector at present. The steel sector generally don't acknowledge the need to achieve a deep cut of emissions. There was not yet any major research research for assessing how steel plants could achieve a deep cut of greenhouse gas emissions until 2016. In the absence of the pilot and demonstration projects in the steel sector in China, the Asian Development Bank (ADB) suggested that new steel plants in China should consider a CCS readiness design (ADB, 2014). Capture readiness (also called 'CCS Readiness") is a design concept to build a new plants with engineering consideration for retrofitting to carbon capture and storage in the future. The most important benefit of the capture readiness design is to avoid the risk of ‘carbon lock-in’ effect. The capture readiness design will also benefit steel companies by offering more flexibility in reducing carbon emissions over the lifetime of a steel plant. In order to understand the benefits, the paper makes a techno-economic assessment of CO2 capture technologies at a hypothetical Chinese new-build steel plant. A steel plant built today could operate for 25 to 40 years, therefore, establishing carbon capture and storage readiness (CCSR) at steel plants can be a low-cost technical approach to ensuring steel plants could have the opportunity to be retrofitted with CCS to achieve significant cuts in greenhouse gas emissions in the future. This study is the first paper investigating CCS readiness in the iron and steel sector. The paper develops a novel linear programming model for assessing the option value of CCS readiness of steel plants in China. The study and the model could be a reference for policymakers and industry stakeholders in considering design options for building new steel plants in China.

2. Literature review

CCS is a process to reduce greenhouse gas emissions from major stationary emission sources, such as thermal power, refinery, cement and iron and steel sectors. The primary benefit of deploy CCS technologies is to reduce greenhouse gas emissions. Some CCS projects could utilise CO2 for industry purpose (such as enhanced oil recovery) which could have a side benefit financially. Given high cost and the energy penalty in the CCS process, the technology has not yet been widely deployed in China. However, as IEA (2017) estimated the role of CCS is essential for climate mitigation in the next 3 decades.

The initial consideration for capture readiness design was to ease carbon capture retrofit and avoid the ‘carbon lock-in’ effect. Gibbins (2004) defined capture readiness as a ‘plant designed to have CO2 capture added at some time in the future with minimal impact on lifetime economic performance’. In the meantime, the physical space is another essential element in any capture readiness proposal to coordinate the additional capture facilities. The concept was further developed in the subsequent years (Gibbins et al, 2006) and is applicable in any kind of capture technologies, both post-combustion capture and pre-combustion capture processes. In

December 2004, the US environmental group Natural Resources Defense Council (NRDC)'s emphasized that 'the development of capture readiness in China for coal gasification based poly-generation' (co-production of electricity and chemicals) listed as one of their national initiatives in its China Clean Energy Project (NRDC, 2004). Wilson and Gibbins (2005) enriched the concept of 'capture readiness' in 2005, especially suggesting that the existing carbon capture plants have to be designed as a capture readiness plant and with proven- and socially- acceptable CO2 storage options.

Capture readiness should not be restricted to capture technologies alone, it must be viewed as an integrated technology which also includes CO2 transportation and storage. For example, plant siting should consider the distance between the plant and the storage site in order to lower the cost of transportation. For newly-built plants, a spectrum of investments and design decisions would be required to be undertaken by the plant owner during the design and construction stages of the plant (Bohm et al, 2007).

The Global CCS Institute (GCCSI) (2010) with support from ICF Consulting further developed the capture readiness concept and promoted CCS readiness as an extended definition of capture readiness with more consideration of storage and transport readiness. Capture readiness was adopted by the UK Government in the revision of the Electricity Act 1989. The concept was brought to China in 2006 through stakeholder consultations in the Chinese Advance Power Plant Carbon Capture Option (CAPPCCO) project (Li et al, 2012) and an option value concept was introduced by Liang et al (2009) for a hypothetical case study of a power plant in China to enable stakeholders to understand the intrinsic value of making a new plant capture-ready.

The concept of capture readiness was also promoted by multilateral banks in China, and the ADB (2014) made a recommendation for capture-ready plants' design in 2014. The Chinese industry incorporated the capture readiness concept in the 2014 feasibility study of China Resources Power Haifeng Project's Units 3 & 4 coal-fired power plant (GDCCUSC, 2014). However, there was no study explicitly focus on making new steel plants in a CCS readiness design.

In summary, the concept of capture readiness has evolved over time, from a narrow appreciation of the basic physical requirements for future retrofit of capture technologies, to a broader understanding of the need to anticipate and support a variety of future CCS-related needs. The concept should not be restricted to 'capture' alone; a CCS project should be regarded as an integrated plant across the full chain of capture, transportation and storage. Accordingly, plant siting should consider the distance between the plant and the storage site in order to lower the cost of transportation. Consideration of reuse existing infrastructure could also lower the cost of retrofit to CCS (Li et al, 2019 Alcade et al, 2019).

3. Methodology

This study is the first to provide a techno-economic assessment of a hypothetical first-of-its-kind (FOAK) CCS project at commercial scale in a newly-built modern Chinese steel production plant. The simulation assumes the use of amine technology to capture the relatively-high concentration CO2 emissions from the iron-making process. The steam and electricity used for operating the CCS project is assumed to come from an on-site supercritical coal-fired power plant. Advanced System for Process Engineering (ASPEN) was used to simulate the technical process, combined with a financial model developed by the authors.

Amine-based scrubbing technologies have been applied in CO2 capture in many industries for many years, such as coal-fired power plants, refinery plants, coal-chemical plants, etc. New types of amines are still being developed and commercially-available amines include some proprietary amines developed by technology providers, as well as conventional amines with open access, such as MEA and MDEA, which are the earliest and most common amine family members used in CO2 separation processes. Compared with MEA, proprietary solvents generally have lower regeneration heat duties and higher CO2 absorption capacities. In general, the CCR requirements of future new types of amine should not be greater than those of current conventional amines. This study will therefore focus on assessing the carbon capture readiness requirements associated with using a generic amine solvent (30 wt% MEA) as the base-case scenario (Abadie and Chamorro, 2008; Junginger, 2010).

The study uses ASPEN software to perform process simulation, which is then used to develop a conceptual design for CCR requirements. ASPEN Plus is a proven chemical process simulation software that has been widely applied for R&D, design of large chemical systems, and production operation optimization of the whole chemical plant. As a powerful engineering design tool, ASPEN Plus can provide engineering design parameters, chemicals consumption and utility requirements. The estimation of the operation cost can be performed based on the outcome of the ASPEN Plus simulation, as a starting point for further technical and economic analyses.

The economics of retrofitting flexibility in a steel plant is a real option problem, because a deterministic net present value may fail to capture the option value of retrofitting involved in the sequential decision-making at each year (Liang et al, 2009). Therefore, the paper applies a real option approach (ROA) with a linear programming model to value the retrofitting option in the steel plant. For economic modelling, the paper applies Excel with and @risk simulation programme with 100,000 trials to estimate the option value of Capture Readiness design.

3.1 Simulation Sample and Assumptions

The study assesses the economics of CCS from a generic crude steel production plant with blast furnace (BF) route, applying the process and financial assumptions of the Baowu Steel Zhanjiang plant (BSZ) in Guangdong, China, as a case study example (Baowu Steel, 2016; Liang et al, 2018) . We assume the plant aims to capture 0.5 MtCO2/year by using a mature amine CO2 capture technology for a newly-built steel plant in 2022.

The BSZ is one of the most design-advanced steel plants in China, with a compact layout, an integrated waste metal recycling unit and a pollution control unit. It is located at Donghai Island in Zhanjiang City, in the west of Guangdong province, and covers an area of 12.98 km2. The plant is co-located with the site of the SINOPEC-Kuwait project, a major petrochemical complex at its development stage. Construction of the BSZ reference plant was completed in July 2016. The total capital investment was CNY 50 billion (USD 7.1 billion). The plant, which has a production capacity of 9.38 million tonnes of steel per year (4.48 million tonnes hot casted and 4.9 million tonnes cold casted), plant was designed by the China Metallurgical Group

Corporation (MCC).

The CO2 concentration in the flue gas is 25%. The flue gas initially enters a cleaning process, then arrives at the amine capture absorber module. After the capture process, the captured CO2 would be compressed before it is transported for storage. In order to reutilize the energy (H2 and CO) in the remaining flue gas, it is recycled to the bottom of blast furnace. The composition of the flue gas is listed in Table 1.

Table 1. Estimated composition of blast furnace flue gas steam

Treated BF Gases	**Units**	**Composition**
CO_2	% (v/v) dry	25%
CO	% (v/v) dry	21%
H_2	% (v/v) dry	3%
N_2/Air	% (v/v) dry	49%
H_2S	mg/Nm^3	10
Particulate Matter	mg/Nm^3	5
Mn	mg/Nm^3	0.2
Pb	mg/Nm^3	0.05
Zn	mg/Nm^3	0.05

3.2 Economic Modelling Methodology

The cost of CO_2 avoidance (CNY/tCO_2) (COA), is:

$$COA = \frac{\sum_{n=0}^{T} \frac{(I_0 + O_n + F_n + S_n)}{(1+d)^n}}{\sum_{n=0}^{T} \frac{(Q_n - A_n)}{(1+d)^n}} \qquad [1]$$

Where

I_0 is the value capital investment cost accumulated to year 0,

O_n is the fixed operating and maintenance cost at year n,

F_n is variable costs at year n,

S_n is the transport and storage cost at year n,

Q_n is the total amount of CO_2 captured from the project at year n,

A_n is the total amount of CO_2 generated from an auxiliary power plant for supplying steam and electricity for capturing and compressing CO_2 at year n,

d is the discount rate (i.e. the required rate of return), and

T is the lifetime of the project.

The main driver for retrofitting the blast furnace with carbon capture is an increase in carbon emission savings related revenue and a reduction of capital and operational cost. The study adopted capital cost reduction and electricity output penalty to represent technology learning rates. These learning rates focus on the capital cost of building a post-combustion capture steel plant and the performance of the CO2 capture process rather than the total cost of separating CO2. The electricity output penalty (EP) of available capture technologies is modelled here by a one-factor learning curve model (Abadie and Chamorrow, 2008;), given by formula 2 as below:

$$EP_n = EP_0\left(\frac{CA_n}{CA_0}\right)^{\log(1-m)} \qquad [2]$$

Where

EP_n is the Electricity output penalty at year n in kWhe/tCO2.

CA_n is Global installed capacity of post-combustion capture power plants at year n

m is the technology learning rate for electricity output penalty

The capital cost of available capture technologies is given by formula 3 as below:

$$I_n = I_0\left(\frac{CA_n}{CA_0}\right)^{\log(1-w)} \qquad [3]$$

Where

I_n is the CCS retrofit investment cost at year n in kWhe/tCO2.

CA_n is Global installed capacity of post-combustion capture power plants at year n

w is the technology learning rate for capital cost

Table 2. Capture plant capital cost assumptions

Variable Cost Components	
Amine Cost (CNY/tonne)	35000
Amine Consumption (kg/tCO2)	1.2
Electricity Price (CNY/kWh)	0.485
Initial Electricity Output Penalty	142
Waste Amine Disposal (CNY/t amine)	500
Water Cost (CNY/tCO2)	6.5
CO2 transport and storage (CNY/tCO2)	112

Table 3. Capture plant initial capital cost assumptions

Capital Cost Components	Million CNY
Total capture plant cost	360.0
Owners costs	25.2
Working capital	16.0
Start-up costs	2.0
Total capital investment in 2022	407.2

Based on the estimate, the current capital cost of the capture plant is CNY 360 million[1] (USD 51 million) with an additional 8% margin for owner's cost (**Table 2**). The project needs CNY 16 million (USD 2.3 million) working capital cost to regulate the development and CNY 2.4 million (USD 0.35 million) to cover start-up costs. The modelling results show an electricity output penalty (EOP) for the auxiliary power plant of 142kWh/tCO_2 captured (**Table 3**) and the EOP assumption was verified by the engineering team. The electricity price of auxiliary power used in the calculation is CNY0.485/kWh (USD 7 cents/kWh) – approximately 10% above the benchmark electricity price in Guangdong which was adopted as a general practice for internal cost accounting in Iron and Steel plant. The price of amine is CNY 35,000 per tonne based on the market price quoted by China Resources Power Haifeng carbon capture project team. The fixed O&M cost is CNY 14 million (USD 2 million) per year estimated by the authors based

[1] The engineering team of China Resources Power Haifeng Carbon Capture Plant provide the estimates.

on the engineering experiences of current CCS project (**Table 4**).

Table 4. Assumptions of capture plant operating costs

Operating Cost Component	Million CNY
Fixed operating costs	
Maintenance	3.00
Operating labour	8.60
Insurance and local taxes	1.00
Other O&M	1.40
Total Fixed Operating Costs	14.00
Variable operating costs (at 90% capacity factor)	
Fuel cost at year 0	34.08
Amine	21.00
Waste disposal	0.30
Water Cost	3.25
Total Variable Costs	**58.63**

From an investor point of view, the value and the exercising strategy of a retrofitting option on the steel plant has been investigated. Uncertainties are drivers of the option value. The stochastic cost cash flow model has been established, and it used option value at each time-step (i.e. year) as the criterion to justify the decision of retrofitting. The ROA decision-making framework is a complex model with Bermuda style claims (i.e. options could be exercised at the end of each year from now to any expiration date). This requires a backward-looking algorithm to find the optimal exercise boundary. A least square regression method with Monte-Carlo simulation has been used to estimate the option value.

In each operating year, there are some options to retrofit an unabated steel plant with CO_2 capture technology. A group of factors would influence the retrofit decisions: electricity price (PE_t), carbon price (PA_t), the expected benefit of retrofit in the present value at year t ($E(B_{R,t})$), the retrofit cost at year t ($K_{R,t}$), and r is the risk free discount factor (at 3.2% in this case[2]). The carbon price and electricity prices follow GBM with Mean Reverting stochastic processes with assumptions given in **Table 5**. The technology learning rate is based on a consultation of five senior scientist with experiences in developing amine carbon capture technologies and

[2] Apply the average Chinese Yuan 10-year sovereign bond yield rate from Jan to Jun 2019.

another five engineers who have experiences in building carbon capture pilot projects in China. The global post-combustion capture capacity and its growth rate assumption is estimated based on a linear approximation based on 5-year data from 2014 to 2018. The carbon price and stochastic variable assumptions were made based on the team's experiences.

Table 5. Assumptions of stochastics factors

Learning Rate for Electricity Output Penalty (m)	5%
Learning Rate for Capture Plant's Total Capital Cost (w)	8%
Global installed post combustion capture capacity in	10 million
Growth rate of post-combustion capture capacity from	22%
Carbon Price in 2022	CNY 100/tCO2
Drift Factor for Carbon Price from 2022	5%
Lognormal Standard Deviation of Carbon Price	20%
Mean Reverting Factor for Carbon Price	20%
Drift Factor for Electricity Price from 2022	0%
Lognormal Standard Deviation of Electricity Price	10%
Mean Reverting Factor for Electricity Price	40%

Assuming the retrofit time is one year, we can use the following Bellman formula to evaluate the value of retrofit option at year t (V_t) :

$$V_t(PE_t, PA_t) = max\left\{E(B_{R,t}) - K_{R,t}, \frac{1}{1+r}E(V_{t+1}(PE_{t+1}, PA_{t+1}))\right\} \quad [4]$$

In this equation, at year t, the plant's life time is N, the terminate value $V_N = 0$. The initial retrofit option value could be estimated as V_0
i.e. the value of making a plant retrofitable at year 0 is equal to the value of retrofit option V_0

The expected retrofit benefit ($E(B_{R,t})$ is affected by electricity output penalty cost, transportation and storage cost and the CO_2 allowance benefit. $Q_{i,R}$ is the net output capacity after retrofit at year i, $Q_0$is the initial plant capacity (i.e. 188.7MW), u is annual utilisation hours (assumed 5000 constantly). The emission factor after retrofit is $H_{i,R}$, the emission factor before retrofit is H_0. GC is the total amount of CO_2 captured at year i, CS_i is the cost for storage and transportation at year i. d is the commercial discount factor (assumed to be 8%[3], reflecting retrofit investment is less risky than current CCS demonstration projects) while the lifetime of the steel plant is T (i.e. 25) as shown in formula 5.

$$E(B_{R,t}) = \sum_{i=t+1}^{T} \frac{[(Q_{i,R}-Q_0)\cdot u\cdot E(PE_i)+(H_{i,R}-H_0)\cdot Q_{i,R}\cdot u\cdot E(PA_i)-GC_i\cdot CS_i]}{(1+d)^{i-t}} \quad [5]$$

The following formula 6 illustrates the main principle of a CCS readiness investment decision making. The decision depends on the retrofit option value difference between with CCR and without CCR scenarios at year 0 (V_0) and the required investment for Capture Readiness (I_{ccr})to make the selected plant retrofitable.

$$\text{Invest, if } V_0 \geq I_{ccr} \quad [6]$$

Notably, in some special cases, the plants may be retrofitable without CCR investment, as only very minor design modification is needed.

3 Apply the discount rate used in Haifeng Carbon Capture Project Feasibility Study.

4. Results

The result shows the CO_2 avoidance cost for a new built steel plant with the capture capacity of 0.5 million tonnes per year is CNY 442.54/tCO_2 (USD 63.22/tCO_2) at 12% discount rate. Over the lifetime of the plant, it would capture 11.25 MtCO_2 in total, 0.45 MtCO_2/year. However, there are some factors that would greatly influence the CO_2 avoidance cost, including the discount rate and the transportation and storage cost. Discount rate is one of the most important factors, Discounting is an empirical economic principle which means that property's economic value in the future are worth less than they are at present. There is also uncertainty regarding future CCS related policies and regulations, especially whether the value of carbon credit is enough to support CCS large scale application. Furthermore, the development of capture technology is uncertain. Therefore, we then test the impacts of different discount rate in the simulation. Different discount rates imply the different level of risks, with higher risk indicating higher discount rate, and the risk is highly related with policy environment. We make a comparison between moderate and high risks. If this investment is considered as a moderate risk, with an 8% discount rate applied, the cost of CO_2 avoidance (i.e. the abatement cost) will be reduced to CNY 407.56/tCO_2 (USD 58.22/tCO_2). In contrast, if assuming the investment with higher risk at a 16% discount rate, the cost would increase to CNY 480.14/tCO_2 (USD 68.59/tCO_2) with an increase of 17%. Despite of different type of manufactory, this simulation result is much larger than the natural gas combined cycle CCS (NGCC-CCS) plants, where the discount rate increased by 8% to 10% results in an increase in the additional costs of the coal plants by 5%.

Generally, CO_2 is transported via pipeline and the costs depend on the length of pipeline, the terrain and the volume of CO_2 transported. In CO_2 storage, the type, depth and shape of the geological formation and the storage process largely determinate the cost, which could be varied plant to plant. Also, it implies transport and storage costs are very case-specific. In this experiment, if the CO_2 storage and transport cost increased from 112 CNY/tCO_2 to 123 CNY/tCO_2 (USD 16 to 18/tCO_2), the abatement cost would be CNY 443.96/tCO_2 (USD 63.42/tCO_2) at a 12% discount rate. Overall, with the setting different premasters, the analysis shows that the cost is ranged from CNY 407 to 480 /t CO_2, which is much higher than the current carbon price in Guangdong, ranging from CNY 20 to 40/tCO2. This indicates the cost-effective hardship in promotion of the investment in CCR in Guangdong provinces.

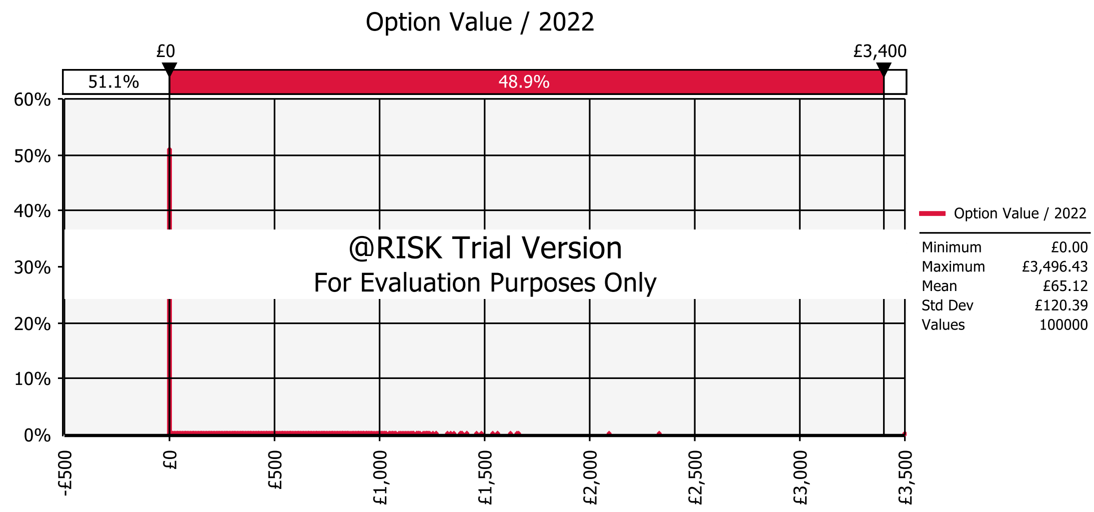

Figure 1. Steel Plant Capture Readiness Option Payoff Schedule at 5% Carbon Price Drift Factor Assumption. X-Axis: Option Value. Y-Axis: Probability Distribution.

On the other hand, the cost of CCR is also on the reduction of electricity output, as its work needs electricity. We found that for a plant with CCR, the electricity output penalty is 29MWh, if the wholesale electricity tariff is CNY485/MWh in 2022 (following a GBM-MR process, with a 0% drift factor, a 20% standard deviation and a 40% mean reverting ratio). When we set the carbon price to be CNY 100/tonne CO2 (following a GBM-MR process, with a 5% drift factor, a 20% standard deviation, a 20% mean reverting ratio) in 2022 and the transportation cost is CNY112/tonne CO2 captured, the average retrofit option value is CNY 65 million (USD 9.5 million), with payoff distribution shown in **Figure 1**. The simulated option payoff in Figure 1 shows there is 51% chance the option payoff is zero, in other word, the retrofit would not happen in this scenario. For the remaining 49% probability, the option payoff varies with the maximum payoff is up to 3496 million. Thus, based on the average retrofit option value finding, if the carbon and electricity prices and technical assumptions are valid, it is commercially viable to invest up to 65 million Yuan (USD 9.5 million) to ensure the base steel plant to be retrofittable for post-combustion carbon capture.

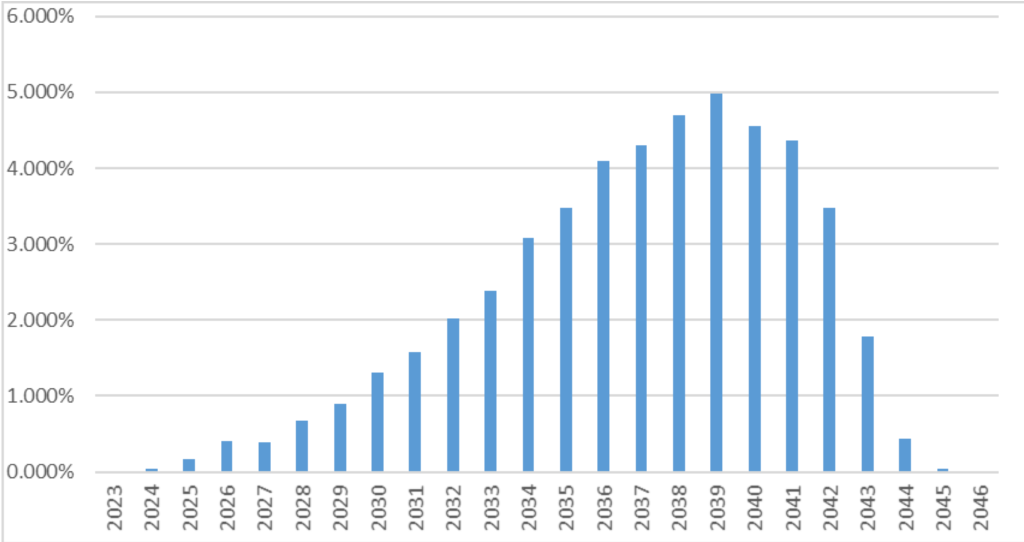

Figure 2. Probability of economic viable retrofit of steel plant to 0.5 million tonnes carbon capture and storage. X-Axis: Year of Retrofit. Y-Axis: Probability of Retrofit.

There is approximately 49% of financially viable probability in retrofit for the lifetime, with the probability of retrofit year illustrated in **Figure 2**. The Option Value is very sensitive to the assumption of carbon price growth (drift factor). The drift factor of carbon price is assumed to be 6%, the option value will be increased to CNY 144.9 million with 78.9% chance of economic viable retrofit to CCS in the lifetime.

5. Discussion

CCR in Iron/steel industry is still not cost-effective to be widely applied in the China. However, CCR in iron/steel industry is rarely seen, where only two large-scale iron/steel CCS projects are currently in operation: the UCLOS (Ultra-Low CO2 Steel Consortium) Project and the Emirates Steel Industry CCS Project (GDCCUSC, 2016). The former is located in France with a capture capacity up to 700,000 tCO2/year from a blast furnace in a steel plant, while the latter is built in Abu Dhabi with a capture capacity of 800,000 tCO2/year from a Direct Reduced Iron (DRI) facility. The Emirates Steel project has started operation but the DRI process is rarely used in the steel sector. There is a lack of experience in capturing CO2 from conventional blast furnace steel making process and flue gas streams from blast furnaces are also in low partial pressure.

As per IEAGHG (2007)'s definition of capture readiness, developers of capture-ready plants are responsible for ensuring that all known factors under their control and which could prevent the installation and operation of future CO2 capture are identified and eliminated. This includes **(a)** Conducting a study of options for CO2 capture retrofit and potential pre-investments; **(b)** Inclusion of sufficient space and access for the additional facilities that would be required; and **(c)** Identification of reasonable route(s) for the storage of CO2. Pre-investment in these essential capture-readiness features is expected to be relatively inexpensive. Further optional pre-investments could be made to reduce the cost and downtime for CO2 capture retrofit.

A key requirement for the construction of capture-ready steel plants that adopts amine capture technology is the reservation of sufficient space onsite to accommodate the additional CO2 capture equipment, plus the ducts and pipes for connections to it and points where the necessary connections to the existing plant can be made. A further requirement is to allow for the extension of additional related requirements (cooling water, auxiliary power distribution, etc.) of the capture equipment. The space required is also discussed in the context of individual systems and equipment, as illustrated in **Table 6**. The building complex includes Distributed Control System (DCS) control rooms, the electrical switching rooms, research laboratories and offices. The utilities and auxiliary facilities could possibly be shared with the steelmaking plant. Other auxiliary systems include a compressed air system, maintenance, and a fire station.

Table 6. Design Requirement for CCS Readiness in Steel Plant

(A) Essential Space and Design Requirement	
For Carbon Capture	Flue gas pre-treatment unit
	CO_2 capture unit
	CO_2 compression and liquefaction unit
	Raw material storage facilities
	Building complex
For utilities & auxiliary facilities	Electrical distribution system
	Cooling water system
	Raw water and desalted water treatment
	Waste treatment and disposal system
Other common facilities	Flue gas ducts
	Pipe racks
	Other auxiliary systems
(B) Further Pre-investment	
Design Consideration	Flue gas desulphurisation (FGD) equipment
	DeNOX equipment
	Particulate removal unit
	Steam sources and waste heat recovery options
	water-steam condensate cycle
	Compressed air system
	Cooling water system
	Raw water pre-treatment plant
	Desalination plant
	Waste water treatment plant
	Electrical equipment
	Chemical dosing systems and steam water analysis system
	Plant pipe racks
	Control and instrumentation
	Safety equipment
	Fire-fighting and fire protection system
	Plant infrastructure
	Steam turbine options for CO_2 compression

As well as satisfying the essential requirements of space, access and a route to the storage site, further pre-investments can be made to reduce the cost and downtime for the retrofit of CO_2 capture. The pre-investments are suitable for many technologies in the plant design, for example, oversizing pipe-racks and making reserved design of the control system and constructing a larger electrical distribution station. These pre-investments are generally low in cost and could significantly reduce the CCS retrofit costs and downtime. Potential pre-investments that could be applied are illustrated in **Table 6**. The current experience of amine post-combustion capture shows a bag filter particulate removal unit is likely to be better for post-combustion capture than an electrostatic precipitator due to improved aerosol removal.

The costs of capture technologies are expected to decrease in the future due to ‘learning by doing’ and incremental technological improvements. If a plant is made capture-ready for a single existing technology, it makes for a higher risk and is locked-in to a technology, thus making the pre-investment worthless. Capture-ready plants should therefore be designed to accommodate anticipated future technological improvements, as far as is reasonably possible, with what is called an open technology design. Based on the estimate by Guangdong CCUS Centre, the estimated total capital cost for a 0.5 million tonne capture is in the range of CNY 10 million (USD 1.5 million) to 14 million (USD 2 million). Nevertheless, it is difficult to predict future technology developments and the risk of obsolescence remains a major reason for not making substantial technology-specific pre-investments.

6. Conclusion

CCS is an important low-carbon technology to decarbonize the steel sector in China. Given the barriers of high cost and high energy penalty, it is difficult to deploy CCS on a large scale in China in the short-term. Although the iron and steel sector in China has significant greenhouse gas emission, there was a lack of CCS pilot or demonstration projects in the iron and steel sector in China. The paper is the first attempt in researching capture readiness design and value in the world. The paper proposed key considerations for first-of-a-kind capture readiness design steel plant and explores the option of pre-investment for making new steel plants capture readiness. With a capture readiness design, a steel plant would be able to be retrofitted to CCS at a lower cost. However, the paper finds the option value of CCS retrofit is CNY 65 million (USD 9.5 million). In other words, by investing in Capture Readiness design for 0.5 million tonnes capture, the economic value of steel plant is increased by CNY 65 million (USD 9.5 million) in their lifetime, significantly higher than the estimated investment for capture readiness design at USD 1.5 to USD 2 million. The capture readiness investment will also avoid the carbon lock-in effect, as the pre-investment would allow the owner of the steel plant to actively consider CCS retrofit option.

In regard to business and policy implications, it would be beneficial if national or regional CCS entities could be set up to coordinate capture readiness planning and inform developers of new steel plants on capture readiness design requirement. It is also beneficial to develop CCS related design standard in China with a particular focus on capture readiness design standard. The introduction of policy incentives options for making new steel plants capture readiness is worth further studied. It is also worth pursuing a technology roadmap for CCS in China with consideration for CCS options in the iron and steel sector. There are a number of limitations to be addressed in the future. The paper makes simplified assumptions on CO2 transport and storage while the route for utilizing or storing CO2 is an essential part of CCS readiness design. The paper assumes a partial capture from blast furnace. The hypothetical project would only reduce the emissions by 0.40 MtCO2/year, or a total of 9.93 MtCO2 in 25 years. More studies should be conducted to assess the viability and the economics of CCS for all emissions sources for the whole steel plant. It is also valuable to assess the value of benefits if all newly built steel plants in China adopt the capture readiness design in the next decade.

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Appendix 1 CCS related policy documents in China

Year	Institutions	CCS Relevant Policy Document
2006	State Council	Outline of the National Medium and Long-Term Science and Technology Development Program (2006 - 2020)
2007	Ministry of Science and	China's National Climate Change Program

	Technology	
2007	Ministry of Science and Technology, NDRC, Ministry of Foreign Affairs etc.	China's Response to Climate Change Science and Technology Special Action
2011	Department of Social Science and Technology, Ministry of Science and Technology	China's Carbon Capture, Utilisation and Storage Technology Roadmap
2011	Ministry of Science and Technology	National "Twelfth Five-Year" Science and Technology Development Plan
2011	State Council	"Twelfth Five-Year" Greenhouse Gas Emissions Control Work Plan
2012	State Council News Office	China Energy Policy (2012) White Paper
2012	National Energy Administration	Coal Industry "Twelfth Five-Year" Development Plan
2013	Ministry of Science and Technology	"Twelfth Five-Year" National Carbon Capture, Utilization and Storage Technology Special Development Plan
2013	NDRC	Notice on Promoting the Demonstration of Carbon Capture, Utilization and Storage
2013	State Council	Opinions of the State Council on Accelerating the Development of Energy Saving and Environmental Protecting Industries
2013	Ministry of Environmental Protection	Notice on Strengthening the Environmental Protection Work of Carbon Capture, Utilization and Storage Test Demonstration Projects
2014	General Office of the State Council	Energy Saving and Emission Reduction Action Plan for Low Carbon Development 2014 - 2015
2015	State Council News Office	Strengthening the Response to Climate Change Action – China's Intended National Determined Contributions (INDCs)

Sources: State Council, 2006; MOST, 2011; NDRC, 2012; MOST, 2013; GDCCUSC, 2016: p. 24